Current Challenges for Industrial Application of LES Turbulence Models

Session: FD-28, Current Challenges for Computational Fluid Dynamics, Industry and Government Interests I

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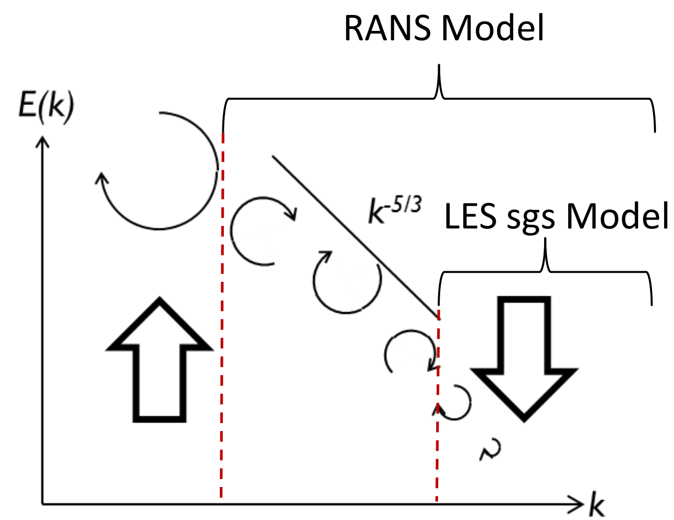
Industry Objectives For LES Modeling

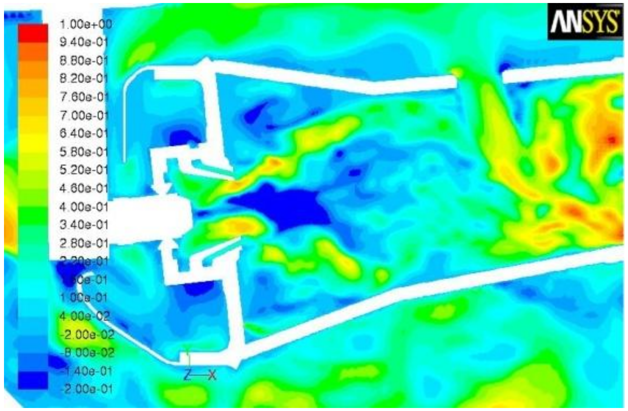
- RANS used routinely for design, test and verification
  - Designed and calibrated to provide time average flowfield
- Time resolved flowfield required for:
  - Quantification of time resolved unsteady behavior
    - Acoustics, ignition, unsteady part loads (e.g. high cycle fatigue (HCF) forcing), structural interactions (e.g. flutter), transient flows (e.g. inlet unstart, aircraft maneuver, take-off), combustion instability, engine operability, …
  - Improved prediction of time mean flows
- Desirable LES characteristics
  - Time mean solution maintained (or improved)
    - Asymptote to RANS solution as space-time resolution is reduced
    - Approach DNS as resolution is increased
  - Generality – no problem or scale specific tuning
  - Improve CFD Fidelity

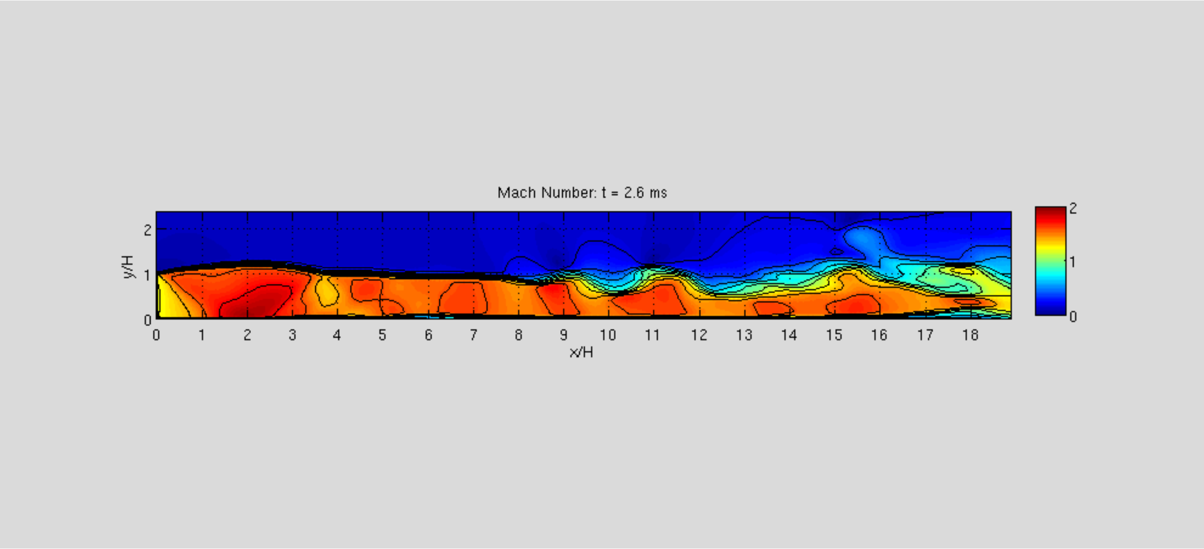


LES is practical today for engineering problems of interest – How do we quantify accuracy and calibrate methods for the engineering design process?

Industrial LES

- Outline
  - Example Problem Description
  - Affordability
  - Accuracy
    - Unsteady Spectra
    - Steady state preservation
  - Reacting Flows
  - Conclusions

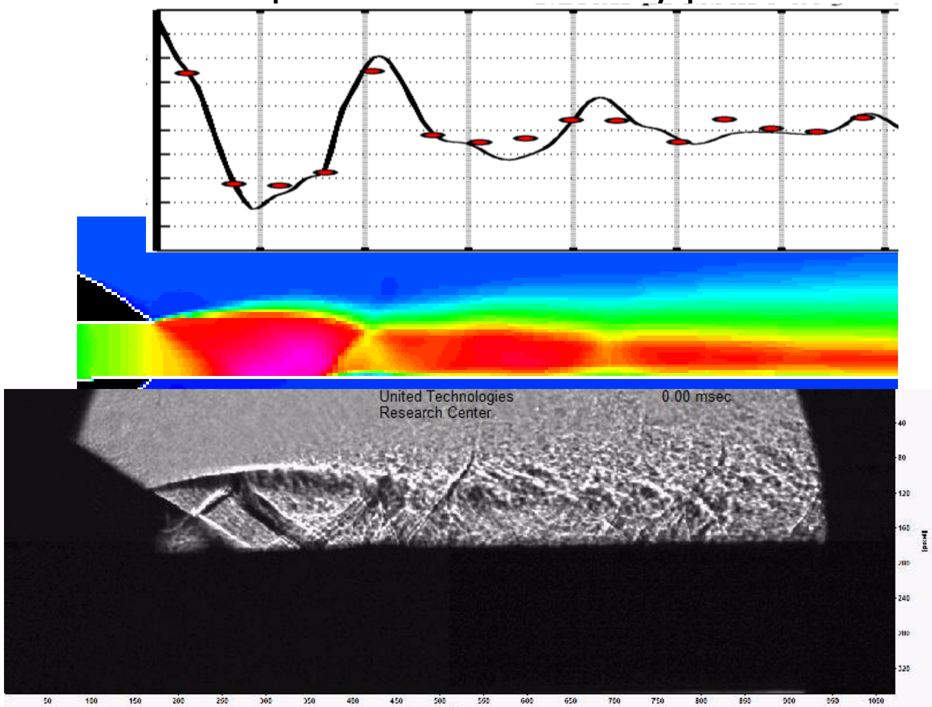


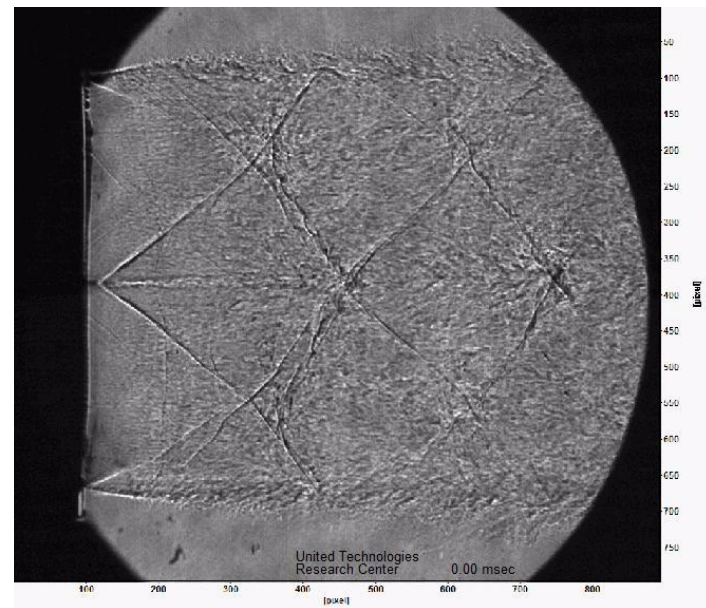


Affordability and Accuracy drive LES relevance to industry

Example Problem – HCF Aeromechanic Forcing

- Determine unsteady pressure on plate behind high aspect ratio nozzle
  - Rich flow measurements available
  - Highly instrumented deck
    - ~50 high response pressure transducers
- Steady RANS captures mean flow
- Can LES predict the unsteady pressure field?





Relatively low frequencies associated with HCF make it a good candidate for initial LES application

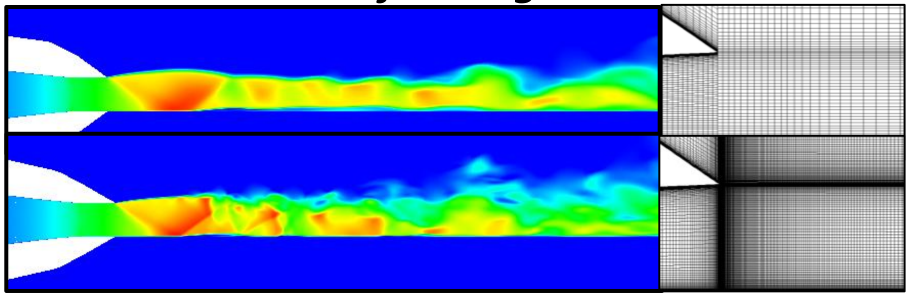
LES Affordability

Today can afford (and RANS typically resolves) isotropic resolution to about 1% of relevant engineering scale (L)

- 10^6 points in an L^3 box
- Dt~L*10^{-5} sec (L in feet, a~1e3 ft/sec)
- f_{max} ~ 10^5/L Hz = 100/L kHz

- These scales are of engineering interest
  - Highest structural modes are on this order (most structures less sensitive above this)
  - Acoustic sources (20-20000 Hz)
- Insufficient resolution for
  - Acoustic propagation to 100L (requires factor of 10^6 increase in cost)
  - Turbulence spectra (<0.01%L length scale – 10^8 increase in cost)
  - Chemically reacting flows
- Doubling resolution increases cost 8-16X, but only gets 2X higher frequency
  - Better RANS and sub-grid models required for foreseeable future

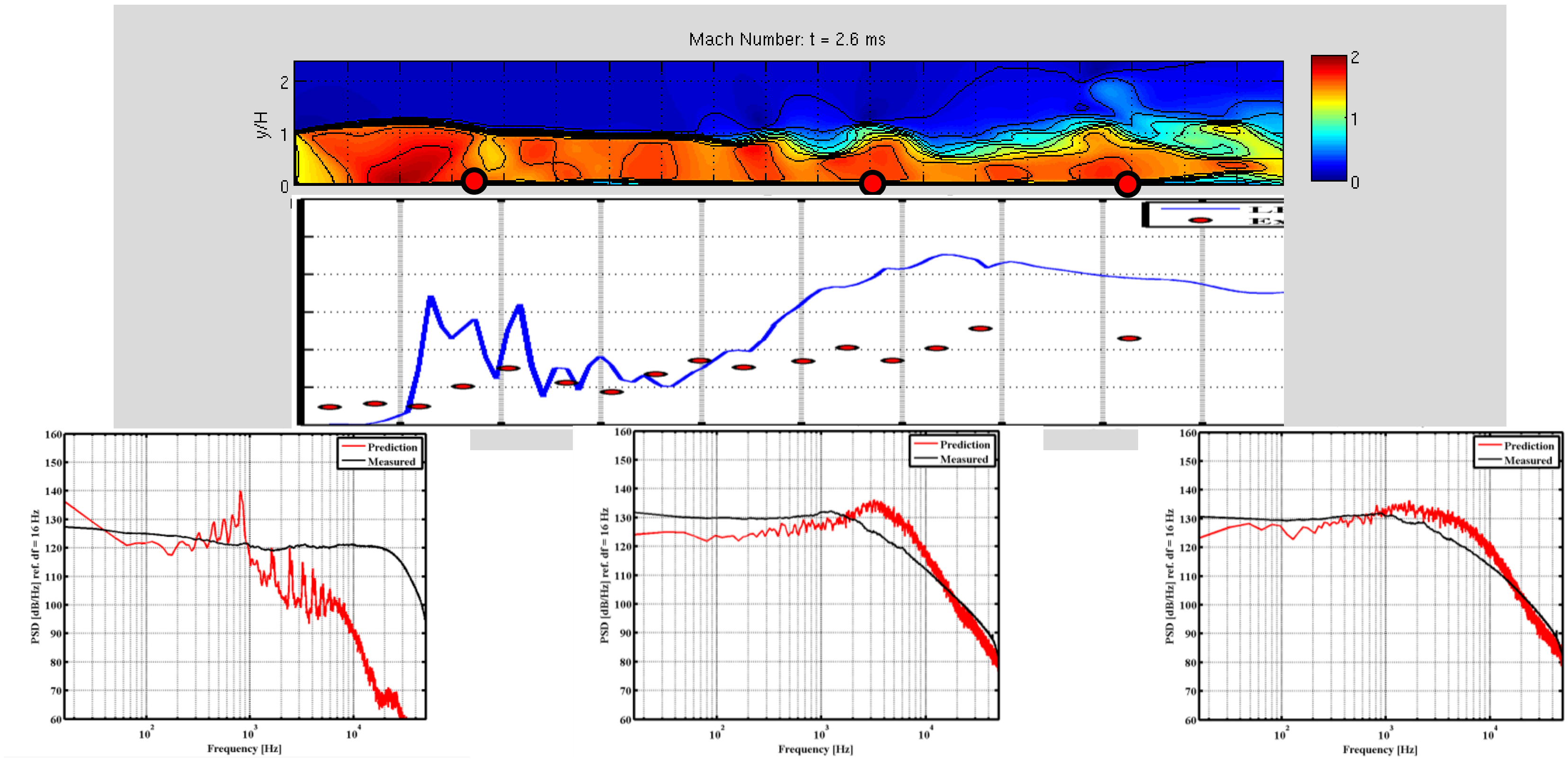
Grid filtering



N^4 operation count ensures RANS and low frequency LES will be the norm

LES Accuracy - Predicted Spectra

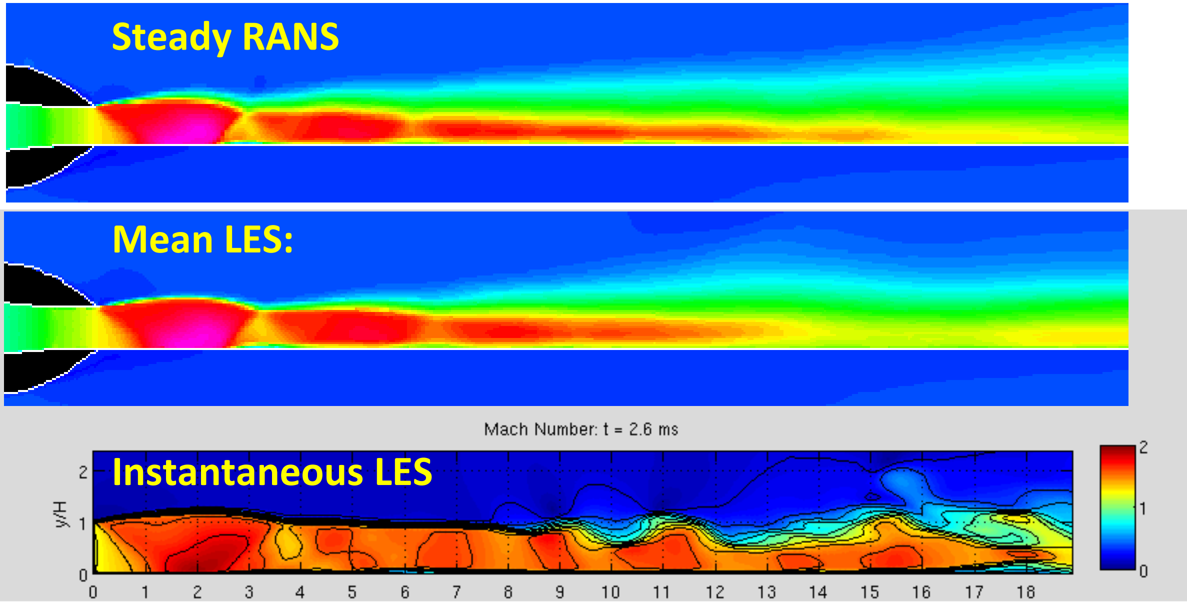
- Resolved spectra comparable with data
  - Downstream spectra driven by larger scales – reasonable accuracy
  - Upstream spectra has more high frequency content driven by smaller, unresolved scales – reduced accuracy

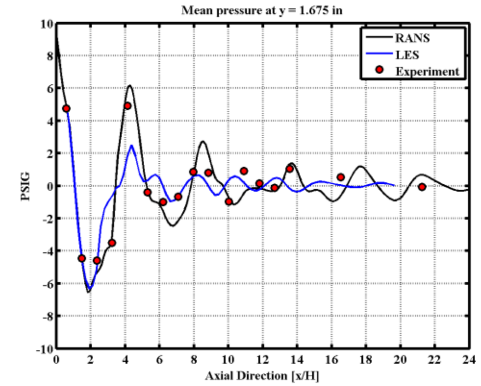


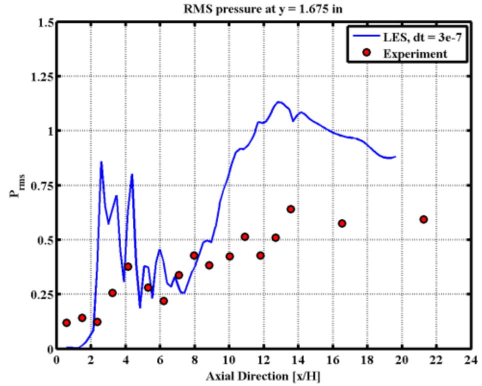
Today's LES capability can predict large scale unsteadiness at un-calibrated accuracy

LES Accuracy - Impact on Mean Flow

- LES may alter the time mean solution
  - Reduced mixing in upstream shear layer (small scales)
  - Changes in mean pressure distribution over the deck as resolution increases
- How do we interpret unsteady results? What aspects are more/less reflective of physics? What inaccuracies are introduced by:
  - RANS model deficiencies
  - Inaccurate calculation of resolved scales
  - Sub-grid models





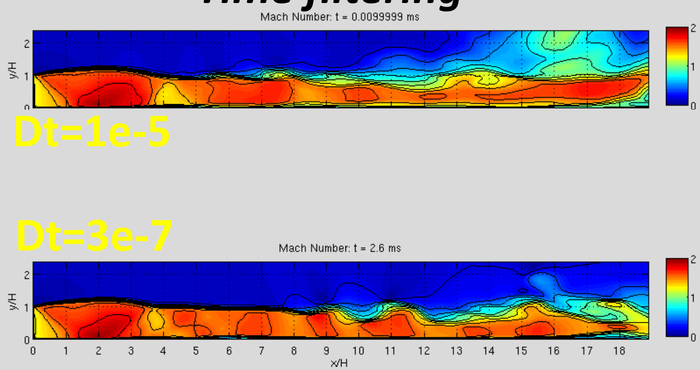


Today's LES has unintended and un-calibrated impact on mean flow predictions

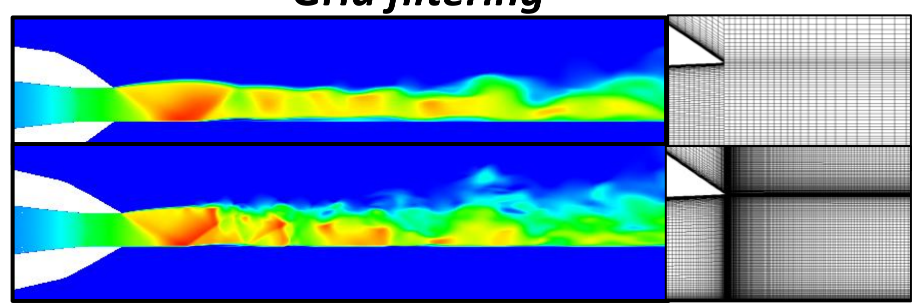
LES Accuracy - Drivers

- Scheme order
  - Impacts accuracy of highest resolved frequencies
  - Higher order schemes allow higher frequencies to be computed on fixed grid
- Grid spacing
  - Increasing isotropic resolution expensive
  - Cost increase goes as n^3
- Time resolution
  - Code boundary layer stability constraints increase cost of spatially resolved frequencies by an order of magnitude
  - As space resolution increases, time resolution will need to increase
  - Total cost for increased resolution goes as n^4

Time filtering



Grid filtering

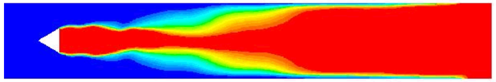


LES accuracy dependent on multiple, inter-related, tunable models and assumptions

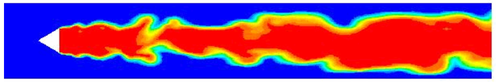
LES Accuracy – Drivers (Cont)

- Boundary Modeling
  - Near wall modeling
    - Near the wall dissipation and energy spectrums overlap
    - Near the wall there are no “universal” small scales to model
    - Hybrid RANS/LES, or LES with DNS resolution is required
  - Inflow Boundary Modeling
    - Inlet turbulence assumptions drive solution
- Turbulent viscosity model
  - RANS and/or sub-grid turbulence model
  - Over dissipation of flow can over-damp resolved scales
  - Under dissipation leads to
    - Under-prediction of the mean flow mixing in poorly resolved regions
    - Over prediction of resolved unsteadiness
  - Improved sub-grid models are required to maintain or improve prediction of mean flow

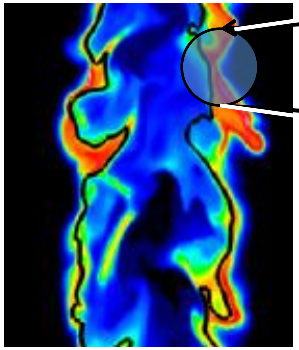
Detached Eddy Simulation

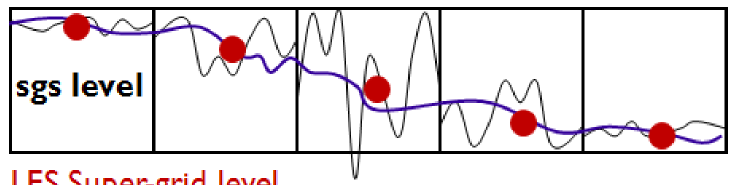


LES Dynamic ksgs



- Reactive Flow Modeling
  - Combustion also occurs on the LES scales (Molecular diffusion, Reaction)
  - Different subgrid scale species variations, which have the same supergrid value will not have the same combustion characteristcs





Chemical Kinetics

$$\dot{\omega}_k = f(Y_k, T, P, \Delta t)$$

$$\dot{\omega}_k \Longleftrightarrow \overline{\dot{\omega}}_k$$

LES Combustion Model

$$\overline{\dot{\omega}}_k = g(\tilde{Y}_k, \tilde{T}, \tilde{P}, \Xi, \Delta t)$$

LES accuracy dependent on multiple, inter-related, tunable models and assumptions

LES Challenges in Industrial Setting

- Challenges
  - Affordability – Can only resolve largest unsteady scales
    - Large scales of most interest for engineering design
    - Better RANS and sub-grid models required for foreseeable future
  - Accuracy – Code independent accuracy quantification needed
    - Mean flow accuracy not maintained as resolution increases – asymptote to RANS solution as resolution decreases
    - Determine accuracy of mean flow as more unsteadiness is resolved
    - Quantify accuracy of predicted spectra
  - Complex Physics

- Directions
  - Resolve more scales as compute capacity and schemes evolve
    - Resolution of all scales not practical or necessary for most engineering applications
  - Need improved methods to process, present and understand unsteady (LES) results
  - Quantify the accuracy of resolved unsteadiness – spectral accuracy
  - Understand the impact of resolved large scales on mean flow prediction
  - Develop models to improve macro (resolved scale) LES predictions as well as the micro (sub-scale) properties is required

Accuracy quantification and calibration of engineering parameters of interest required for reliable use of LES in design processes